Changes in Jupiter's 13-cm Synchrotron Radio Emission Following the Impact of Comet Shoemaker-Levy-9

M. J. Klein, S. Gulkis, S. J. Bolton

Jet Propulsion Laboratory
California Institute of Technology
Pasadena California 91109

ABSTRACT

Results of an observing program to monitor the synchrotron radio emission from Jupiter's inner radiation belts before, during and after the impact of Comet S1 .-9 are reported, The observations were made at 2295 Ml Iz as part of the NASA -JP1. Jupiter Patrol, a long-term radio astronomy monitoring program begun in 1971. The data indicate that the intensity of the synchrotrons emission at 13 cm wavelength increased by 27 percent within a few days after the comet impacts; the longitudinal beaming curve was distorted during the week of impacts; the magnetic latitude beaming curves flattened after the week of impacts suggesting an increase in the emission at higher magnetic latitudes; and the decay of the enhanced emission is consistent with an exponential with a time constant of -125 days. The reported changes following the S1 .-9 impact are unprecedented in the Xl-year history of the Jupiter Patrol.

IN'1'RO1)IJCI'1ON

The spectacular impacts of fragments of periodic Comet Shoemaker-Levy-9 provided a rare opportunity to study the response of Jupiter's radiation belts to a series of energetic perturbations. Responding to predictions that the comet fragments would impact Jupiter in

July 1994, preparations were made by radio astronomers worldwide to monitor the synchrotron emission that dominates the planet's microwave spectrum at decimetric wavelengths. The research reported in this paper is part of the NASA-JPL Jupiter Patrol, a long-term radio astronomy monitoring program begun in 19-/1 (Klein et al 1972). The Jupiter Patrol observations have consistently been made at **2295 Mllz.(13** cm wavelength) several times a month in the first decade and several times a year in recent years. The observing program was intensified in January 1994 in response to the impact predictions for the following July.

The Jupiter Patrol data have shown (Klein et al 1989) that synchrotron emission from relativistic electrons trapped in Jupiter's inner radiation belts exhibit long term variability with timescales of weeks to months. Bolton et al (1 989) have presented evidence of a possible correlation with solar wind parameters. The observations reported in this paper were performed to investigate the properties of the radiation belts by measuring possible effects of the comet impacts.

THE OBSERVATIONS

The observations began in December 1993 to establish a set of baseline measurements in advance of the predicted encounter in July. The first set of observations were made with the Goldstone 70-m antenna on ten dates between December 26, 1993 and March 27, 1994. Beginning in June a 34-meter antenna located at the Research and Development site at Goldstone was used because it would be more available than the 70-m for the intensive observations that were anticipated during the summer months.

The measurement procedures were similar at both sites. Both receiving systems were operated as total power radiometers using a method (Stelzried and Klein 1994) that intersperses system calibrations with traditional OFF-ON-OFF measurements of Jupiter and calibration radio sources. This method has proven to be superior for precision flux density measurements of strong sources, like Jupiter, where systematic errors tend to dominate the receiver-noise errors that randomly affect the detection of weak sources. Small corrections are routinely made for gain variations, system nonlinearities, antenna pointing errors and for the partial resolution of source structure by the antenna beam. The algorithm of de Pater et al (1995) was used to correct for the partial resolution of the thermal and non-thermal components of Jupiter's microwave emission. The factor for the 70-m antenna ranged from 1.()()5 to 1.025 as the planet's distance varied during the year.

In the final analysis, the precision of the average flux density measurements was three percent or better on all days reported here. The precision of data from the 70-m antenna was typically better that two percent as a result of its larger collecting area.

The intensity measurements of Jupiter were calibrated relative to the flux density scale established by Baars et al (1977) and updated by Ott et al (1994). The radio sources Virgo A, 3C 286 and 3C295 were used as primary calibrators and 1127-14 was a secondary calibrator. The respective flux densities for these sources at 2295 MHz and epoch 1994.5 are 138.64 jy, 11.50 jy, 14.31 jy and 4.66 jy.

VARIATIONS IN JUPITER'S SYNCHROTRON EMISSION

The Synchrotron Beaming Curves. The intensity of Jupiter at centimeter wavelengths is comprised of thermal emission from the atmosphere and synchrotrons emission from energetic electrons in the planet's magnetic field. The atmosphere radiates with an equivalent temperature of 305 K at 13 cm wavelength (dc Pater and Massie 1985) and the corresponding flux density at 4.04 au is 2.02 jy.

The synchrotron component is known to vary as the geometry of the radiation belts changes with Jupiter's rotation. When the intensity of tbc synchrotron emission is plotted against System III longitude, the familiar cloublc-peaked beaming curve is produced. An example of the beaming curve early in 1994 tx'fore the cometary encounter is shown in Figure 1. The data points represent a composite set of measurements taken on several nights to acquire coverage of all System 111 longitudes. The dashed curve is discussed below.

Figure 1 near here

Each point represents the non-thermal flux from a single pair of OFF-ON-OFF measurements taken in the azimuth and elevation coordinates. Each flux measurement was multiplied by a normalization factor, $f_d = (d/4.04)^2$ where d is the distance of Jupiter from earth in astronomical units (au). Next the thermal component (2.02 jy @ 4.04 au) was subtracted and the residual non-thermal component was multiplied by a polarization adjustment factor f_p to account for the slight difference between total flux and the flux measurements, which were made with circular polarized feeds (RCP 34-m; LCP 70-m).

The circular polarization of Jupiter's synchrotron emission varies with longitude and magnetic latitude but is never large ((). 988< f_p <1.012).

The observations from the Goldstone 70-m antenna were used to d~'rive a standard beaming curve that could be used as a pre-encounter *template* 10 aid in the search for possible changes following the cometary impacts. It has been shown (de Pater and Klein 1989; Klein et al 1989) that the shape of the synchrotron beaming curves at centimeter wavelengths can be adequatel y represented by equations of the form:

$$S = S_0 + S_1 + S_2 \sum A_n \sin [n(\lambda + \lambda_n)] \qquad (1)$$

where S is the total flux density normalized to a planet-earth distance of 4.04 au, S_0 is the thermal component originating in the planet's atmosphere, S_1 represents a mean value of the synchrotrons flux and S_2 is a scale factor for the ter ms of the Fourier series that represents the synchrotron beaming curve. The coefficients A_n and λ_n have been found to be stable over the 23-year history of the Jupiter Patrol with values that vary predictably with the paramter DC, the Jovicentric declination of the Earth.

Jupiter observations using the 70-m antenna in the winter and spring of 1994 were divided **into** two composite data sets and least squares solutions were calculated for S 1, S2 and the constants An and λ_n for n= 1,2,3. The average values of the coefficients from the two data sets arc listed in '1'able 1:

Al = 1.()()()	λ_1 = 237.98 degrees
A_2 = 1.061	λ_2 = – 66.86 degrees
A_3 = (). 190	λ_3 = 8.55 degrees

S0 = 2.02 jy is the thermal emission described above and the average values S 1 and S2 arc 4.300 +/- ().()24 jy and ().444 +/ ().()04 jy. These values apply for the interval Dec 26, 1993 and Mar 29, 1994 and they arc used along with 'l'able 1 to calcuate the "template" beaming curve shown by the dashed curve in Figure 1.

Average Flux Before the Comet Impacts The average flux for each day was calculated for the Goldstone data by fitting the template beaming, curve to the Goldstone data using the coefficients in '1'able 1 and solving for the best fit values for S 1 and S2 . Monitoring the average flux values, represented by the term S 1, replaces the tradition of monitoring the average fluxes of the two emission peaks that occur during each rotation period when Jupiter's magnetic equator sweeps across the observer's line of sight from Earth. This

approach was selected by several observers (see dePater et al 1995) to provide accurate estimates of the mean value of the synchrotrons flux over the lo-hour rotation period in the event that the beaming curve might be distorted by "hot spots" of increased emission localized in system III longitude. This approach turned out 10 be especially useful during and after the impact period in July.

The values of S 1 and **S2** were remarkably stable over the six month period leading up to the first impact on July 16. The average values of S 1 and S2 from **June** through the first two weeks of July were S]= 4.290 +/- ().()26 jy and S2= ().449 -t/- 0.()()8 jy. Periodic checks of the beaming curves over the same interval showed no departures from the *70-m template* curve. Observations of the 13-cm beaming curve on 15 July showed no signs of change just twelve hours before first impact.

Average Flux Following the Comet impacts The first Goldstone observations of Jupiter following the onset of impacts were preempted by other scheduled experiments until 2230 UT on 20 July when a significant increase in the flux density was immediately noted. Measurements were then made on successive dates between 20 July and 28 July, and drift curves of the planet were made on several dates to search for evidence that the increased flux might be the result of a spatial coincidence of Jupiter and a background radio source in the antenna beam. Within a few clays it was clear (Klein and Gulkis 1994) that the flux increase was caused by Jupiter itself, and that the 13-cm flux increase peaked on July **23.**

The complete sc(of Goldstone observations from the 70-m and the 34-m radio telescopes are shown in 1 'igure 2. The data points represent the S 1 values of the non-thermal flux for each date. Each data point is an average of 20 **to 4(I** individual measurements that typically spanned four to six hours of the 10 hour period of the beaming curve. (Note that Jupiter's declination was too far south to provide northern observers with view periods much greater than six hours with the planet >20 degrees above the horizon.) The relative error on each data point is approximately +/- 1.5 percent.

Figure 2 near here

Figure 2 shows the sudden increase in Jupiter's flux density during the week of the impacts. Maps of Jupiter's thermal brightness at 3.6 and 6 cm wavelength (dePater et al 1995) support the conclusion that the increase was in the synchrotrons component, and not the thermal component, of Jupiter's microwave emission. If this conclusion is correct,

Jupiter's synchrotron flux at 13-cm increased ?.7 percent during the week of the cometary impacts. The results of similar increases at other wavelength are summarized by dc Pater et al (1995) who report that the increase was proportionally greater al higher frequencies, i.e., Jupiter's microwave spectrum "hardened" during the week of the impacts.

The Goldstone measurements show a period of high emission followed by a monotonic decline beginning in August and continuing through October when observations were interrupted by Jupiter's conjunction with the sun. The decline in the 13-cm flux is consistent with an exponential with a time constant of approximately 125 days. Measurements of this decay curve will resume in January 1995.

The Beaming Curve Following the Impacts The synchrotron beaming curves taken in late July were found to be distorted when compared with the pre-encounter curves. On different dates some longitudes appeared to be brighter than the template fluxes but there was no apparent cohcrcncc with respect to fragment impact times. By early August the curve shape seemed to return to normal when plotted as a function of System 111 longitude.

1 lowever, subtle changes emerge when the intensity data are plotted as a function of magnetic latitude rather than System III longitude. For this technique {see Roberts and Komcsaroff (1 965); Roberts and Ekers (1968)) it is assumed that the synchrotron emission is dominated by the dipole component of the magnetic field and that the intensity will primarily be a function of the magnetic latitude of the observer. The change in intensity with magnetic latitude is a function of the distribution of the pitch angles of the electrons at the magnetic equator, i.e., electrons with pitch angles at 90 degrees (flat helices) will be sharply beamed at magnetic latitude zero whereas those with pitch angles < 90 degrees will radiate at higher latitudes.

The magnetic latitude of the Earth, φ, relative to a Jovian dipole tilted at angle β to the planet's axis of rotation, is given by

$$\text{Sin}\ (\varphi) = \text{Cos}(\beta)\text{Sin}\ (D_e) + \text{Sin}\ (\beta)\text{Cos}(D_e)\text{Cos}(\lambda_{III} - \lambda_{nmp}) \qquad (2)$$

where De = declination of Earth as seen from Jupiter, and λ_{nmp} identifies the system III longitude when Earth and the dipole are coplanar and the northern magnetic pole is tilted toward Earth. **A** good approximation for equation (2) is

$$\varphi = D_e + \beta \mathrm{Cos}(\lambda_{III} - \lambda_{nmp}) \quad (3)$$

When the Goldstone data were plotted vs. magnetic latitude φ, the post encounter curves were noticeably flatter, which suggests that the emission became relatively brighter at higher magnetic latitudes. An example is shown in Figure 3 where the data of July 29 arc compared with the pre-encounter data taken in March. The dashed curve represents the relation $S = S(0)\mathrm{Cos}^N(\varphi)$, where S(()) is the observed non-thermal flux density at magnetic latitude zero and the best fit values of N for the March data arc N=4.9 for (- 14.5 $< \varphi <$0) and N=8.7 (for 0$< \varphi <$7). The north-south assymetry in the steepness of the beaming curve is commonly observed and it is known to vary with De, which is a parameter of the viewing geometry. In contrast, the representative post-encou nter data (July 29) exhibit a flatter slope suggesting that the emission is relatively brighter at higher magnetic latitudes. The best-fit value of N on July 29 was -3.2 for both positive and negative values of φ.

Figure 3 near here

The flattening of the magnetic latitude beaming curve is noticeable in the first measurements taken after the onset of the collisions and appears to persist well into the month of August. This trend can be seen in Figure 4 where the best-fit values of N for (- 14.5$< \varphi <$0) are plotted against UT day-of-year number. Each data point represents a least-squares fit to a complete 1 O-hour beaming curve made up of two adjacent observing dates. The dashed curve in Figure 4 represents the average value of N=5.02 (-14.5 $< \varphi <$0) for the pre-encounter observat ions. The best-fi[values of N for the northern magnetic latitudes (0$< \varphi <$7) indicate a similar flattening but the data exhibit a larger range of scatter. The average values before July 16 and after July 24 are, respectively, N=7.8+/- ().6 and N=4.5 +/- 0.6.

Figure 4 near here

The scatter of the data in Figure 4 is large enough that it is apparent that data from several independent beaming curves are required to capture tr ends in the run of N vs. date. Wc note that the decrease in N is nearly conicident with the peak of the flux curve (hat occurred about July 23 (approximately a week after the onset of the impacts). Furthermore, the minimum value of N, which corresponds with the maximum flattening of the beaming curve, occurred around **August** 13 (day number 22.5). These delays of six to thirty days

between the initial impact dates and the beaming curve changes could prove [0 be useful parameters to discriminate among competing physical models.

DISCUSSION

The observations reported in this paper indicate that the intensity of' Jupiter's synchrotrons emission at 13 cm wavelength increased by 27 percent within a few days after the comet impacts. A sudden increase of this is magnitude and timescale is unprecedented in the 23-year history of the NASA-JPL Jupiter Patrol. Specifically, the data base is void of variations greater than ten-percent with timescales less than a month.

Other changes in the characteristics of the synchrotron emission were also noted: (1) the longitudinal beam ing curve was distorted during the week of the comet fragment impacts; (2) the magnetic latitude beaming curves flattened suggesting a preferential increase in the emission at higher magnetic latitudes; (3) the increase in the synchrotrons emission decayed from early August through late October according to the expression $AS = 1.\ 1(c^{-t/125})$, where AS is in janskys (normalized to 4.04 au) and t is the number of days from July 31, 1994.

The rapid increase of flux density following the SL-9 impact implies that significant changes have occurred in the population of relativistic electrons surrounding Jupiter. These changes could be related to changes in the rate of radial diffusion, local accelerations of electrons, or by a redistribution of the steady state relativistic electrons. Using the combined information gained from maps with high spatial resolution, beaming curves, and polarization measurements obtained by the numerous observers , it should be possible to dccidc which of these alternatives will expain the observational results. 1 Iowever, there is a growing perception that the variety of postulated mechanisms that rapidly accelerate electrons to relativistic energies or that modify inward diffusion models may be insufficient to explain the observed effects of S1.-9. As a result, mechanisms for redistributing pitch angles of the steady sate electrons is beginning to receive serious attention.

Bolton and Thorne (1995) suggest an hypothesis that a localized mechanism scatters the electron (distribution in pitch angle and they demonstrate that the effects of such scattering are consistent with an increase in emission intensity, localized hot-spots in longitude and a hardening of tile spectrum if the scattering is energy or pitch angle dependent. They

suggest whistler mode wave scattering as a potential mechanism and speculate that an increase in wave activity was stimulated by the comet impacts.

ACKNOWLEDGMENTS

The research reported in this paper was performed by the Jet Propulsion Laboratory, California Institute of "1'ethnology, under contract with the National Aeronautics and Space Administration. The extensive observations of the 1994 Jupiter Patrol would not have been possible without the dedicated support provided at Goldstone by the Radio Astronomy and Radar Group and the technical staff at the Venus Development Site.

FIGURE CAPTIONS:

Figure 1. The beaming curve of Jupiter's synchrotron mission at 2295 Ml Iz (λ 13 cm) before the Comet SL-9 impact. Data were taken with the NASA 70-m antenna at Goldstone, CA bet wccn 27 February and 29 March 1994; dashed curve represents Equation 1 with S_1=4.30 jy, S_2=0.444 jy and the coefficients from Table 1.

Figure 2. The intensity of Jupiter's synchrotrons emission at 2295 Ml Iz normalized to a distance of **4.(M** au. Data points represent daily estimates of average synchrotrons component S 1 from equation 1. The thermal component S_0 =2.02 jy was subtracted from each measurement.

Figure 3. Beaming curves showing magnetic latitude dependence o f Jupiter's synchrotron mission at 2295 MIIz before (March) and after (July 29) the impact of S1.-9. The heavy dashed curve in both panels represents the expression $S \propto Cos^N(\varphi)$ with N=4.9 for $\varphi < 0$ and N=8 for $\varphi > 0$. The dashed curve passing through the July 29 data is the best fit curve with N=3.2 for ($-14.5 < \varphi < 0$).

Figure 4. Measurements of the parameter N derived from the magnetic latitude beaming curves of the Goldstone data using the expression $S \propto Cos^N(\varphi)$ for southern magnetic latitudes ($-14.5 < \varphi < 0$). The dashed line represents the average value of N (and $\varphi < 0$) from December 1993 though July 151994.

****

REFERENCES:

Baars, J. W. M., R. Genzel, I.I.K. Pauliny-Toth, .and Witzel, The Absolute Spectrum of Cas A; An Accurate Flux Density Scale and a Set of Secondary Calibrators, Astron. Astrophys., **61,** 99- I(M, 1977.

Bolton, S. J., S. Gulkis, M.J. Klein, I. dc Pater, and T.J. Thompson, Cm-relation Studies Between Solar Wind Parameters and the I Decimetric Radio Emission From Jupiter, J. Geophys.Res., **94**, No. Al, 121-128,1989.

Bolton, S. J., and R. M. Thorne, Assessment ot Mechanisms for Jovian Synchrotrons Variability Associated with S1.9, Geophys. Res. I ætt.. (this issue) 1995.

dc Pater, I., Radio Images of the Planets, Annu. Rev. Astron. Astrophys.,**28**:3347- -99, 1990.

de Pater, 1., The Significance of Microwave Observations for the Planets, Physics Reports 200, No. 1, 1-50, 1991.

de Pater, 1., C. Heiles, M. Wong, R. J. Maddalena, M. K. Bird, O. Funke, J. Neidhoefer, R. M. Price, M. Kesteven, M. Calabretta, M.J. Klein, S. Gulkis, S. J. Bolton, R.S. Foster, S. Sukumare, R.G. Strom, 1-?. S. LePoole, T. Spoelstra, M. Robison, R.W. Hunstead, D. Campbell-Wilson, T. Ye, G. Dulk, Y. Leblanc, P. Galopeau, E. Gerard, A. Lecacheux: The Outburst of Jupiter's Synchrotron Radiation Following the Impact of Comet P/Shoemaker-Levy 9, submitted to Science, 1995.

de Pater, I. and S. 'T'. Massie, Models of the Millimeter-Centimeter Spectra of the Giant Planets, Icarus 62, 143-171, 1985.

Hunstead, R and D. Campbell-Wilson, Periodic Comet Shoemaker-Levy 9 (1993e), IAU Circular 6038, July 27, 1994

Klein, M.J. and S. Gulkis, Jupiter and Comet 1993e, IAU Circular No. 6042, Smithsonian Astrophysical Observatory, July 30, 1994.

Klein, M. J., S., Gulkis and C.T. Stelzried, Jupiter: New evidence of long-term variations of its decimeter flux density, Astrophys. J. Lett. 176, 1.85-1,88, 1992.

Klein, M. J., and I. de Pater, Time Variability in Jupiter's Synchrotrons Radiation, Pmt. of the Workshop on Time-Variable Phenomena in the Jovian System, Lowell Observatory, 25-27 August 1987, NASA **SP-494**, 139, 1989 .

Ott, M., A. Witzel, A. Quirrenbach, T.P. Krichbaum, K.J. Standke, C. J. Schalinski and C. A. Hummel, An updated list of radio flux density calibrators, Astron. Astrophys. 284, 331-339, 1994.

Roberts, J. A. and M. M. Komesaroff (1965), "observations of Jupiter's Radio Spectrum and Polarization in the Range from 6 cm to 199 cm" Icarus **4**, pp 127-156.

Roberts, J. A. and R. D. Ekers (1968), "Observations of the Beaming of Jupiter's Radio Emission and 620 and 2650 Mc/see", Icarus **8**, 1 60-165.

Stelzried, C. 'T'. and M.J. Klein, Precision DSN Radiometer Systems: Impact on Microwave Calibrations, Proceedings of the IEEE, 82, No. 5,776-787, May 1994.

****

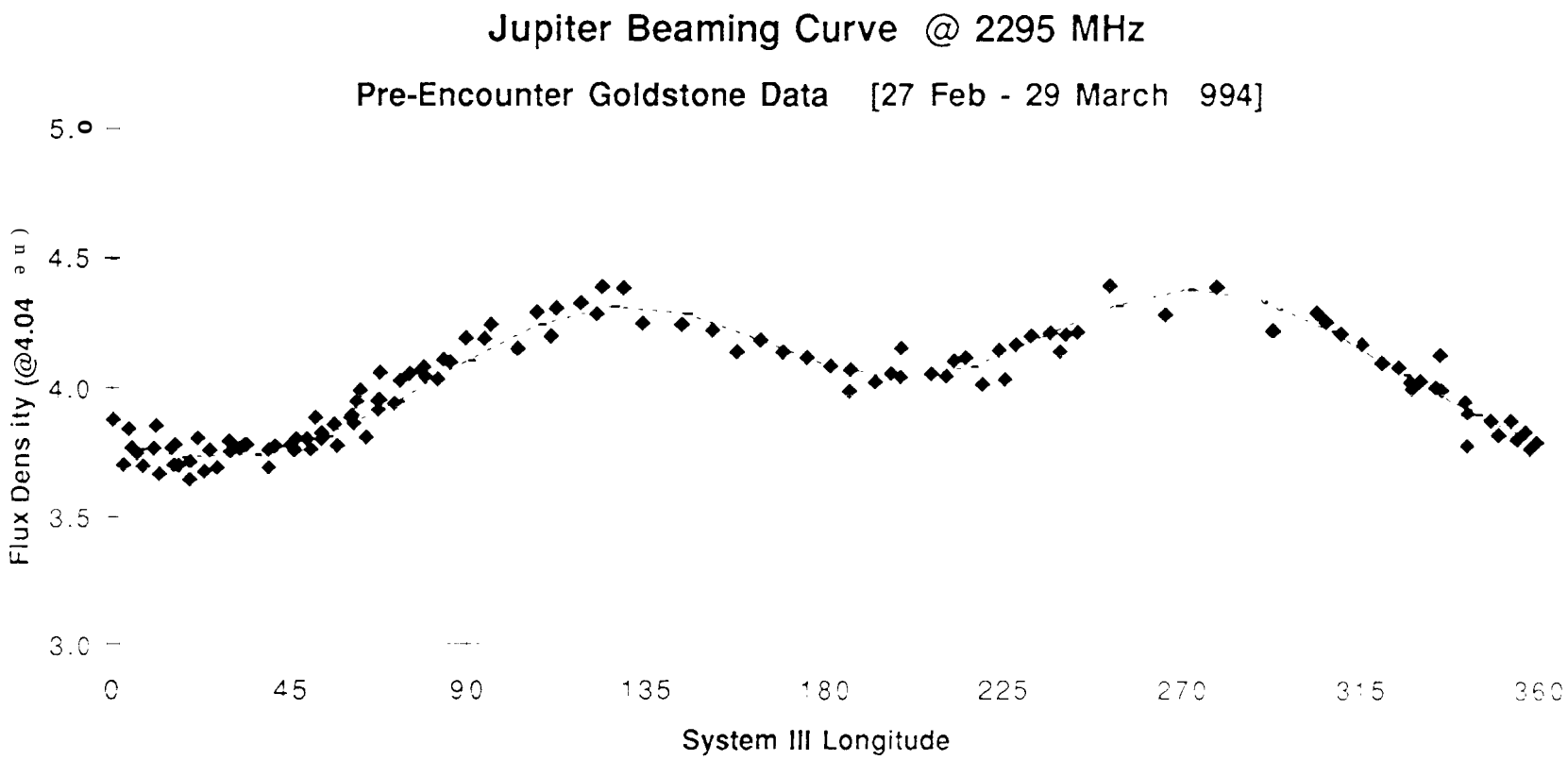

FIGURE 1

MJK 12/9/94

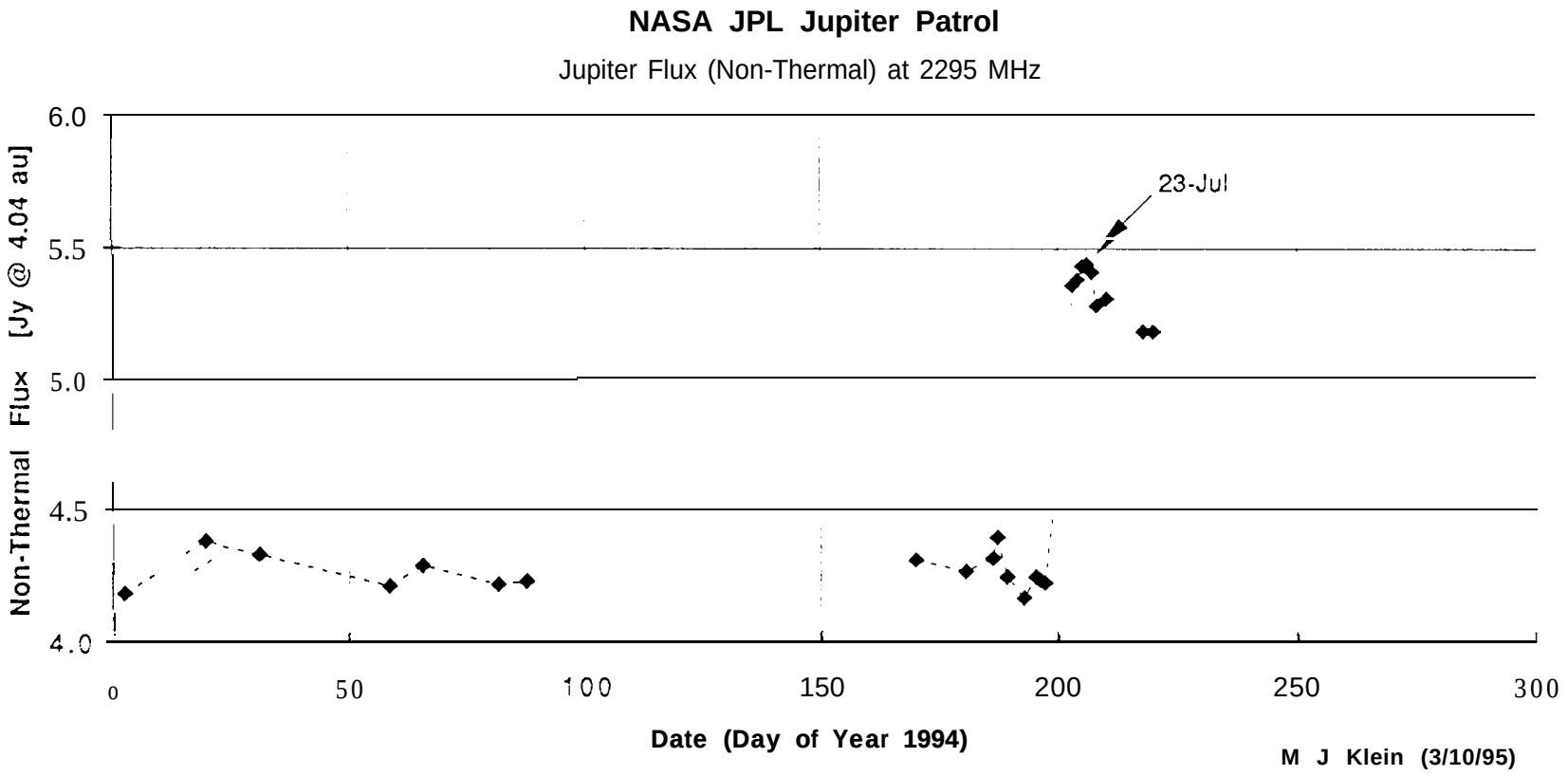
NASA JPL Jupiter Patrol
Jupiter Flux (Non-Thermal) at 2295 MHz
Non-Thermal Flux [Jy @ 4.04 au]
6.0
5.5
5.0
4.5
4.0
23-Jul
0
50
100
150
200
250
300
Date (Day of Year 1994)
M J Klein (3/10/95)

FIGURE 2

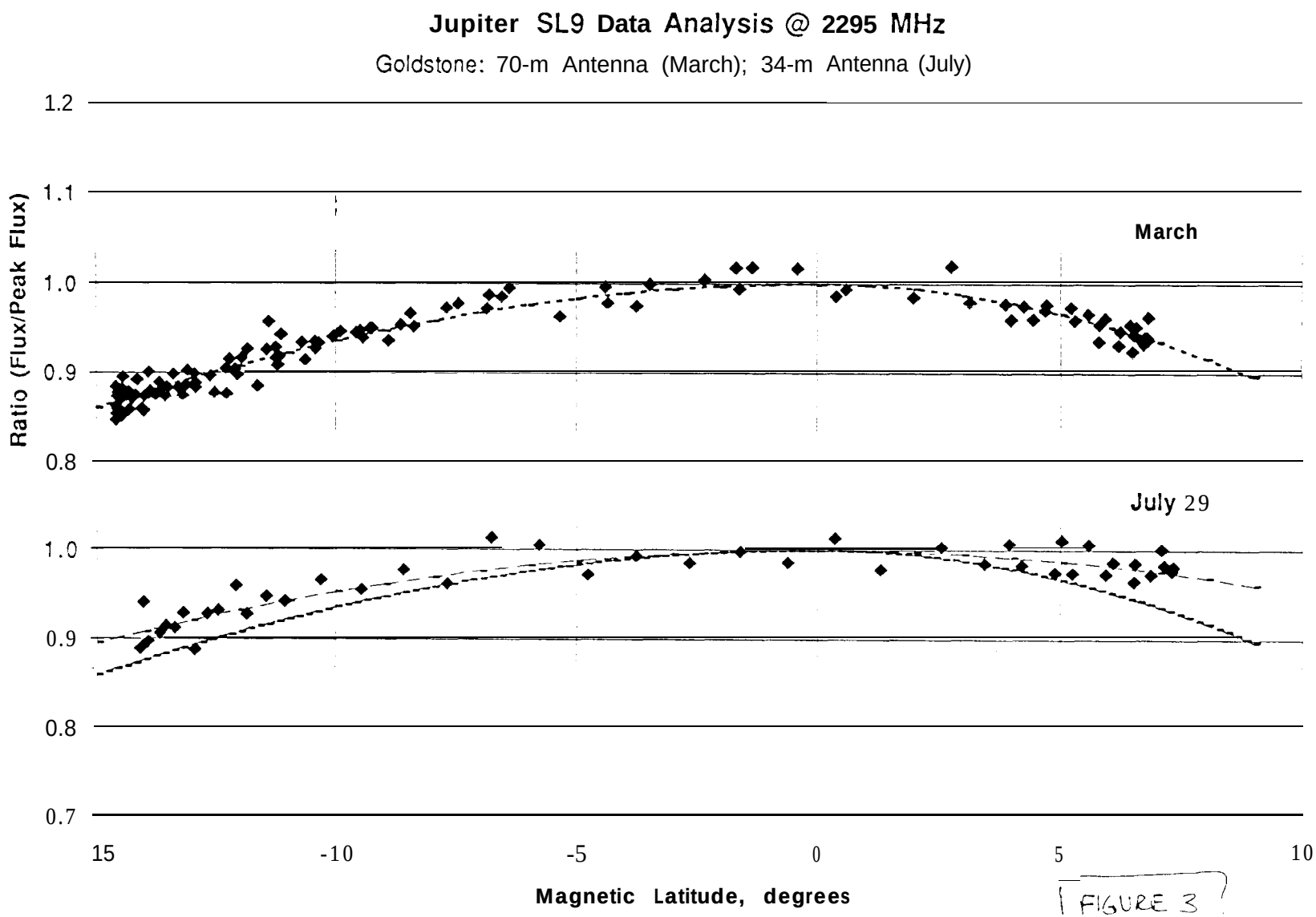
Jupiter SL9 Data Analysis @ 2295 MHz
Goldstone: 70-m Antenna (March); 34-m Antenna (July)
Ratio (Flux/Peak Flux)
1.2
1.1
1.0
0.9
0.8
March
July 29
1.0
0.9
0.8
0.7
15
-10
-5
0
5
10
Magnetic Latitude, degrees

FIGURE 3

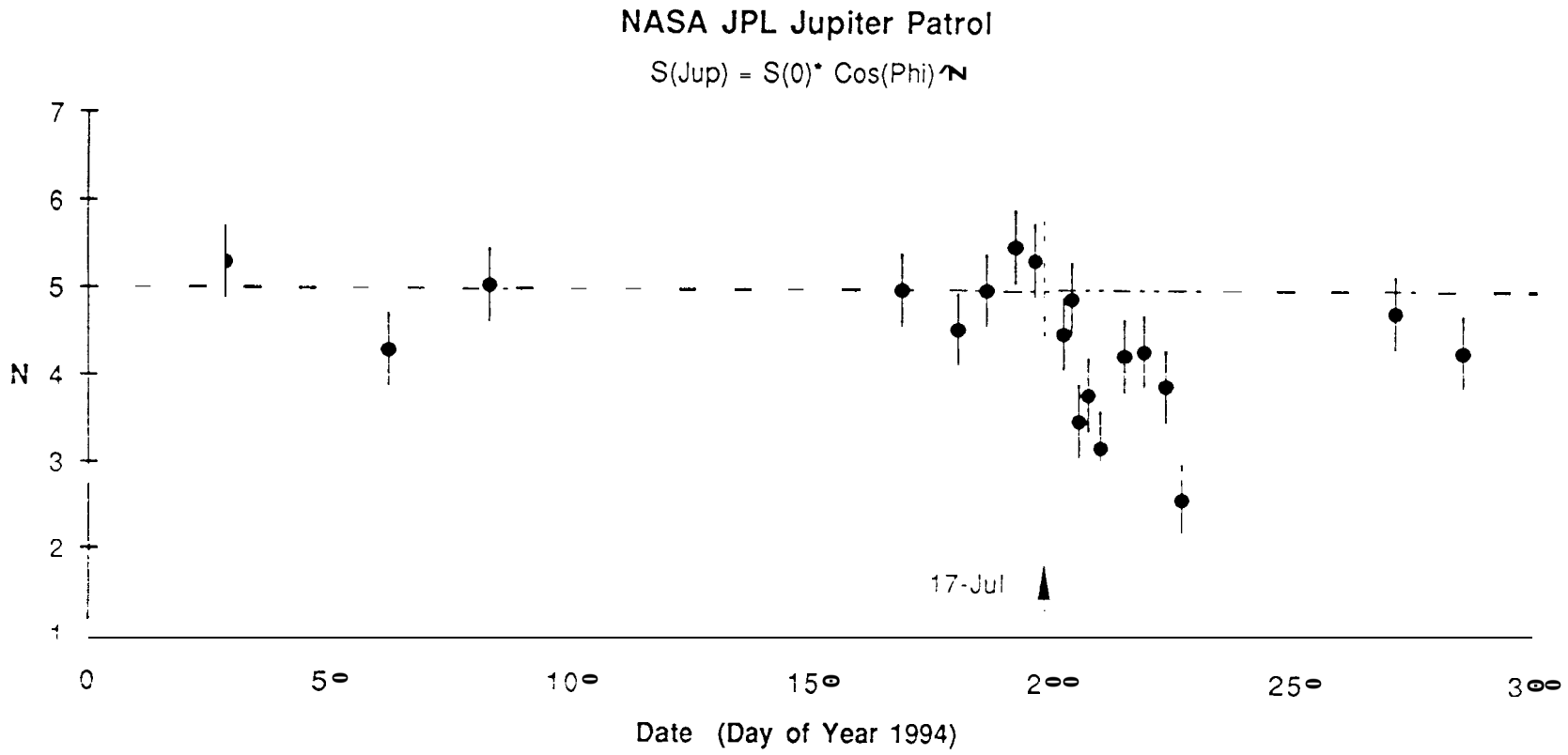

FIGURE 4

MJK 3/14/95